Ultra Lightweight Composite Replica Mirror Technology

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Abstract

We report on the development of extremely lightweight composite replica mirror technology. The technology is maturing at a very rapid pace, and we expect it will soon have an important impact on a new generation of uv-vis-ir telescopes in space and on the ground. Accomplishments to date include the following: total absence of fiber print through and bond lines, vacuum and cryogenic stability, areal density 6 kg/m^2 at 0.9m aperture, figure accuracy 1/20 wave rms (632.8nm) in small flats and fractional wavelength rms in curved mirrors, a large area (4.6m^2) reflector array made with a single mandrel, almost exact reproduction of mandrel microroughness, and active figure control.
We report progress in several revolutionary, technological breakthrough techniques currently under development. These new techniques promise to make possible the low cost and timely production of large concave aspherical replica mirrors with high quality optical figures and supersmooth surfaces, fabricated **without** the need for expensive mandrels. We also report on the development of extremely lightweight meter class mirrors with areal density less than 2 kg/m^2.

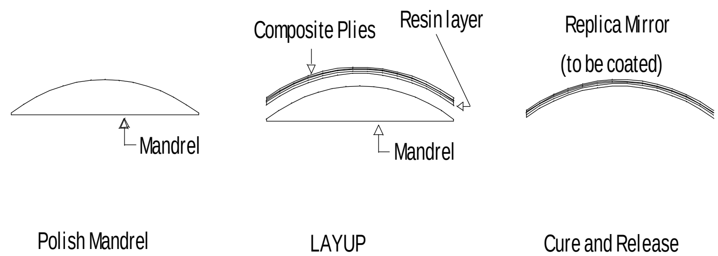
1. Introduction

We report progress on the development of an exciting and rapidly maturing lightweight optics technology. This technology, namely graphite fiber composite mirrors made by optical by replication, is fast approaching realization of its many potentials. It promises to make available in the near future very large aperture telescopes with excellent figures, supersmooth surfaces, quite possibly the lowest areal density, and unprecedented low cost. The availability of these advanced optics is expected to have a major impact on space borne and ground based telescopes, as well as make possible many totally new applications.

2. Composite Replica Mirror Fabrication

Composite mirrors are a new class of super lightweight, super smooth surface optical mirrors. They are fabricated by replication using graphite fiber cyanate resin composite materials. The process is shown in fig.1 below:

Fig. 1. Composite Replica Mirror Fabrication



Graphite fiber cyanate ester resin composite systems have many attributes which make them a superior optical substrate material for space and ground. Among these are low density, high stiffness, low thermal expansion, vacuum stability, stability at cryogenic temperatures, and high radiation tolerance. They are non-toxic, nearly non-hygroscopic, space flight qualified, cheap and widely available from many commercial sources, and easy to work into large complex forms in thin layers. The history of graphite fiber composite optics development, as well as the properties of the specific materials chosen in the CMA process, have already been discussed in literature.[1]

3. **Summary of Results**

We briefly list some of the significant achievements in the development of composite replica mirrors. More details are available elsewhere[1,2,3]

* Space qualified, stable composite material with extremely low moisture absorption and outgassing
* Very smooth surfaces (<10 nm rms microroughness), free from fiber print-through
* Figure accuracy of λ/20 rms over 90% of aperture, 0.2 wave rms overall (@632,8nm)
* Areal density (mass per unit area) 2 to 5 kg/m^2. *This is far lower than the HST (180 kg/m^2) and other lightweight mirror technologies currently being developed for the NGST (15-25 kg/m^2)*
* Aperture to 0.9 m (36") diameter
* Compatibility with SiC and Al/MgF_2 coatings (for high uv reflectivity)
* No bond lines for apertures up to 0.9m daimeter
* Demonstrated long term stability in an observatory environment (28x20" elliptical flat, in use since 1993 as tertiary mirror of the Steward Obs./Max Planck Institute 10 m Arizona SubMillimeter Telescope on Mt. Graham, Arizona)
* Demonstrated stability in vacuum and at cryogenic temperature (77^o K)
* No significant change in microroughness after ion milling
* Elimination of astigmatism by active figure control
* Construction of a prototype athermal, all-composite telescope
* Completion and operation of a 16 segment 1.5m x 2.5m mirror array, where all segments have been made using a single spherical mandrel
* Construction of a prototype solar power array for DoD space applications

4. Solving the Mandrel Problem

Making a concave mirror by replication requires a convex mandrel. However, the fabrication of convex mandrels by traditional techniques is both expensive and time consuming. If supersmooth surfaces are required as well, as they are in our program to develop instrumentation for space uv astronomy, the mandrel costs fast become prohibitive. The lack of even moderate size (20-80cm diameter) mandrels of good quality has until recently been the major impediment to progress in composite replica mirror technology. The mandrel problem is common to all replication techniques, and its solution will be of tremendous importance to the fabrication of 2m and larger mirrors for space flight. CMA is currently addressing this problem with some degree of success.

To give an idea of the magnitude of the problem, we list below some costs with which we are familiar:

Table 1. Typical Costs of Concave Mirrors and Convex Mandrels

Diameter (cm)	Convex/ concave	Shape	Optical figure (6328Å)	Surface finish (Å rms)	Cost
15	Concave	Sphere	1/8 wave	50	$ 150
15	Concave	Sphere	1/10 wave	5	$ 1,500
15	Convex	Sphere	1/10 wave	5	$ 5,000
100	Convex	Parabola	2 μ	5,000	$ 75,000
100	Convex	Parabola	¼ wave	50	$250,000

As can be seen in table 1, convex mandrels are much more costly than concave mirrors. One reason for this is the fabrication effort. It is very much more difficult and demanding to grind and polish convex shapes accurately. Another important factor is ease of testing. Concave mirrors converge light. The surface shapes can be easily characterized using well known and inexpensive methods (Foucault, Ronchi, Hartmann, etc). Convex mandrels, on the other hand, diverge light. Unless the substrate is transparent and can be viewed from the backside, there are only a limited number of ways to test convex shapes (viz. Hindle, matching surface, computer generated holographic test pattern) and they are all expensive (Malacara)

Another important factor to consider is fabrication time. The fabrication of a 15cm convex spherical glass mandrel by a well known and respected optical vendor required three months from start to the ~7Å rms. To go from 7Å rms to 5Å rms took an additional 30 hours or so of shop time. It is clear that, with traditional glass fabrication, the projected costs and fabrication times of multi meter convex mandrels with smooth surfaces quickly become prohibitive.

CMA is developing composite double replication to overcome the mandrel problem. The process is depicted in fig. 2 below:

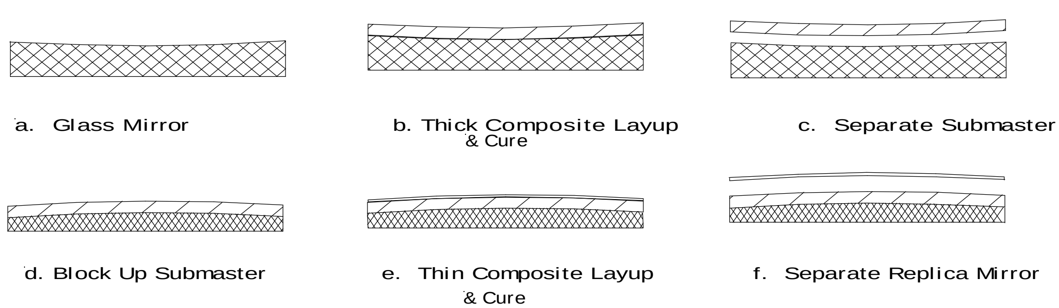


Fig.2 Composite Double Replication

Composite double replication starts with an existing concave mirror (a). A composite laminate, much thicker than is usually used in the fabrication of replica mirrors, is layup upon the mirror (b). The laminate is cured and then released to make a meniscus submaster (c). The submaster is blocked up with appropriate supports on its concave side (d). The convex side is used as the mandrel to fabricate a thin composite mirror in the usual manner.

By using a concave mirror to make a concave replica, composite double replication avoids the high cost and long fabrication times of fashioning convex mandrels. Concave mirrors are easier to fabricate and test. In addition, many large concave mirrors of parabolic or hyperbolic shapes already exist and are readily available. Optical testing of the convex submaster is easy and straightforward with double replication, as will be shown in a moment. And finally, many submasters can be made from a single master before the master needs reworking due to surface erosion. This permits a very significant reduction in the tooling cost.

CMA is making rapid progress in the development of the composite double replication process. Fig. 3 shows the result of our first iteration. The original (left) in this case is a diamond turned aluminum hyperbolic secondary mirror for an infrared cassegrain telescope. It weighs 380 gm. The composite replica (right) is made of graphite cyanate material and weighs 98 gms,resulting in a weight saving of 74%. The figure of neither has been measured since the primary mirror of the telescope has not been available. The exercise was undertaken to work out the details of the composite double replication process, and to demonstrate that submasters can be made from diamond turned aluminum parts.

Fig. 3. A diamond turned aluminum convex hyperbolic mirror (l) and its replica ®

A second iteration is currently in progress. Fig. 4 shows some preliminary results. The master in this case is a 20cm diameter glass parabolic mirror. The interference fringes are formed with the composite submaster resting on top of the master. The assembly is viewed from below through the polished backside of the glass in sodium light (589.3 nm). It is evident, without going into detailed analysis, that the reproduction accuracy is good as can be seen by the straightness of the fringes. The important point is that this technique permits rapid verification of the quality of the convex submaster and its proper support before proceeding to the final phase of concave replica fabrication. A detailed report and analysis of the data will be presented when done.

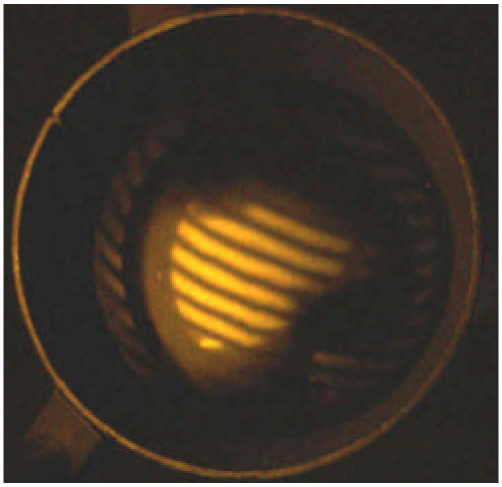


Fig. 4 Interference Fringes Formed Between the Composite Submaster And The Glass Master, Viewed In Sodium Light (589.3nm)

5. Post Figuring

CMA is developing a number of post figuring techniques that enhance the figure accuracy and surface smoothness of composite replica mirrors. The undertaking is motivated by several factors:

a. Large mirrors with extremely high figure accuracy are required for future space UV missions. Mandrels, whether convex or concave, are rare and expensive at such very demanding levels. New techniques are necessary to make very high quality mirrors that are affordable for future small (SMEX and UNEX class) missions.
b. Optical replication, no matter how precise, cannot be exact at the $\lambda/20$ level where λ=1000Å. Some loss in figure accuracy is inevitable. The losses are expected to be compounded in double replication processes. Some means must be found to restore or even improve the as-manufactured figures of replica mirrors.
c. The major objective for future space missions is the search for planets around other stars with large aperture telescopes and interferometers. These telescopes require extremely smooth surfaces in order to reduce scattering from the central star. As the data in table 1 indicates, supersmooth optics are extremely expensive and time consuming to fabricate.

Post figuring is a common procedure in modern glass optics. The Keck telescope mirror segments, for example, were polished to the $\lambda/20$ (optical) level and then post figured to the $\lambda/100$ level by ion milling[4]. It may be possible to apply the same technique to refine the optical figure of composite replica mirrors. A preliminary study has found that composite mirrors could be ion milled without significant increase in surface microroughness[1]. Investigations are currently under way to develop the ion milling process for precise figuring of composite mirrors.

A variety of other procedures are being investigated as well. The optical surface of composite replica mirrors made by the CMA process is a thin layer of cyanate ester resin, an organic compound. It should be possible to use chemical etching processes to selectively remove material up to several microns thick for figure improvement. Other chemical reactions may be initiated that can create ultrasmooth resin surfaces. A number of trial runs have been made which yielded very encouraging results. The investigation is still at an early stage. More details will be presented as they become available.

6. Progress in Making Extremely Lightweight Optics

Following a suggestion by A. Meinel (NASA JPL), CMA undertook a study to study the feasibility of extremely lightweight optical mirrors that can be rolled up for launch and then unfurled for deployment. The idea has the merit of simplicity. Typical rocket fairings can accommodate payloads up to 4m in diameter. Larger telescope mirrors will normal need to be made in segments which are then assembled for deployment. The deployment mechanism, as well as the supporting structures and actuators needed to precisely position the segments and maintain figure, significantly add to the mass, complexity, and cost of a mission. On the other hand, if a monolithic rollup mirror can be made that can meet the performance specifications, it would be a very important advance in telescope technology. The new technology may eventually lead to the realization of kilometer size mirrors in space.

Composite replica mirror technology is a promising candidate for this application. Replica mirrors are made by applying multiple layers or plies of composite prepregs to a mandrel. The number of plies can be varied, and hence the laminate can be made either thin or thick depending on the application. Ply orientations can also be varied to make the laminate stiffer in some preferred directions and more flexible in others.

Preliminary trials carried out by CMA are shown in the figures below. A 0.9m thin replica mirror was made by replication against a glass mandrel. The mirror substrate is a six ply laminate. It was found that the mirror could be rolled up and unrolled several times without taking a set (fig. 5). No cracking was observed after a dozen rollup-unroll cycles.

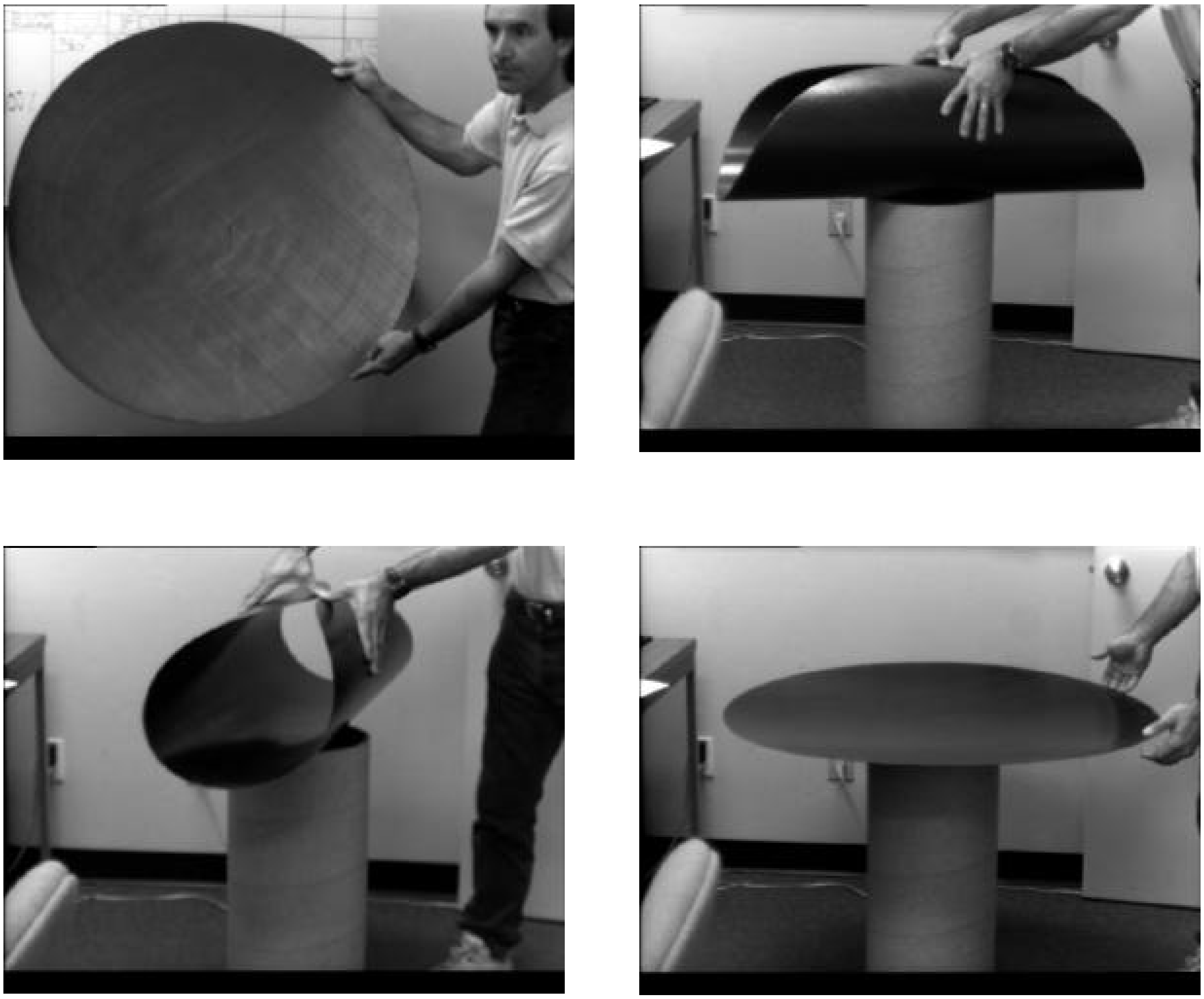


Fig. 5. Demonstration Of A 0.9m f/1.2 Super Lightweight Rollup Mirror

Preliminary data to date show that a rollup telescope mirror is feasible. Much more work remains to be done, especially on the optical surface quality and deployment and actuation mechanisms, before the concept can be considered truly viable. The preliminary trial does illustrate the versatility of the composite replication technology. At an estimated areal density of less than 1.5 kg/m^2, the prototype rollup mirrors shown in figs. 5 & 6 (below) are certainly amongst the lightest of lightweight telescope mirrors.

Fig. 6. Second Iteration of A 0.9m Diameter Rollup Mirror

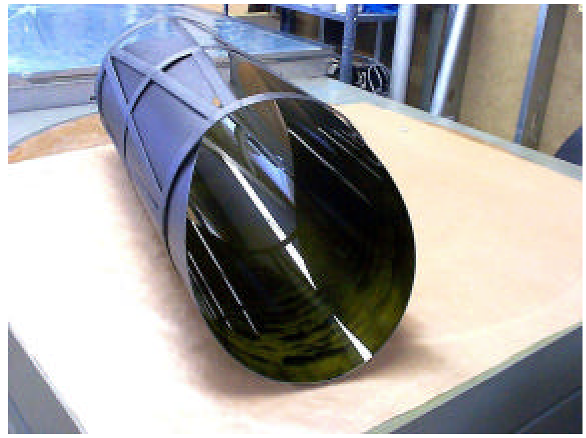


Figure 6 shows the results of a second iteration at making a flexible rollup mirror, this time with a smooth surface. Tests of the optical figure accuracy were made by resting the replica mirror concave side down against the mandrel. The interference fringes were recorded by viewing through the backside of the glass mandrel in the light from a sodium discharge lamp. The replica was then removed from the mandrel, rolled up and unrolled several times, and put back onto the mandrel. No changes were observed in the fringe pattern, which indicated that the replica mirror had excellent figure retention. The results are very encouraging and represent a significant step towards proving the viability of the large flexible mirror concept.

6. **Conclusion**

Composite replica mirror technology is maturing at a rapid pace. It is already being used in a number of non-imaging applications in industry and research. With the development of advanced techniques such as composite double replication and post figuring, the goal of achieving large aperture, very lightweight, and diffraction limited optics is within reach. The development is expected to have a major impact on all types of space and ground optics. Many new applications will likely become possible. A good example is the furturistic idea of space telescopes with rollup mirrors.

7. **References**

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